METHOD AND SYSTEM FOR AUTOMATED CONVERGENCE AND FOCUS VERIFICATION OF PROJECTED IMAGES

BACKGROUND OF THE INVENTION

1.   FIELD OF THE INVENTION

5   The present invention relates to the field of projection displays and more specifically to the automated measurement of such displays.

2.   DESCRIPTION OF THE RELATED ART

The convergence and focus of projection displays

10 having more than one spatial light modulator (SLM) are typically determined subjectively by an operator. As a result, repeatability and tight tolerances in converging and focusing many projectors are difficult to accomplish. The results often depend on the skill and motivation of

15 the person making the adjustments.

Figure 1 illustrates the convergence issue in a three-micromirror projection display (used for example only). The three micromirrors, each dedicated to one of the three primary colors of light (red, green, and blue),

20 respectively are embedded within the optical system of the projector. The images from these three micromirrors are combined by means of combining prisms and as a result, require mechanical alignment so that corresponding pixels from each array lay exactly on top

25 of each other.   Figure 1a shows the same pixel from each of the red 1, green 2, and blue 3 micromirrors. In this

out-of-convergence example, where the green 2 pixel is the reference, the red 1 and blue 3 pixels are shifted relative to the reference green 2 pixel as shown in Table 1 below.

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Table 1

	X	y
R	−0.4	−0.2
G	0	0
B	+0.2	+0.2

It is clear from the figure that this system needs to be converged, at least in the area of the observed pixel.

10   This is best illustrated by the picture of Figure 1b, which shows the unaligned red 1 and blue 3 pixels relative to the reference green 2 pixel. (Note: these show up as fuzzy edges in this B/W illustration, but as mis-aligned color pixels in a color photo). In the

15   actual color picture, the non-convergence is best observed along the edges of the pixel where a blue leading edge is seen at the top and right edge of the pixel and a red trailing edge is seen at the bottom and left edge of the pixel. Typically, an operator would

20   adjust the x and y locations of the red 1 and blue 3 micromirrors until the three images align with on another and the system is converged, resulting in a white image.

Focus is another parameter where the adjustment by an operator is often made subjectively. This parameter

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is more complicated to properly adjust, with many

variables involved. For example, brightness can affect

the focus significantly. In a projection system, focus

is usually accomplished by means of the projection lens,

5   which can be either a zoom or fixed focal length lens.

Figure 2 illustrates a row and column of pixels from a

three-micromirror projection system, which is clearly

out-of-focus. Typically, the projector's operator will

adjust the projection lens to provide the best focus,

10   according to his desires.

Figure 3 shows a row and column of pixels that have

been both converged and focused manually by an operator.

This shows the image properly converged, with the red,

green, and blue pixels being properly aligned so as to

15   appear as one pixel, white in color, and with sharp edges

around both the pixel and around the hole in the center

of the pixel. This hole in the center of the pixel is

where the support post for the micromirror attaches to

the mirror.

20   What is needed is an objective method for

convergence and focus criteria along with a measuring

tool for implementing the method. This method needs to

reflect the human element since the human eye is the

final arbitrator in a display application.   The

25   invention disclosed herein addresses this need by means

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of both a method and a tool.

SUMMARY OF THE INVENTION

The method and system disclosed in this invention

provide an objective tool for measuring the convergence

and focus criteria of a projected image. In addition,

5   lens aberrations caused by lateral color shift are

programmatically corrected.

To converge the red, green, and blue images from a

projector, snapshots are taken at several locations

across the field-of-view. Data from each of these

10   snapshots is separated into primary color images

(typically red, green, and blue). The centroid of an

identical row and column in each of the three (red,

green, and blue) images is measured and the differences

in the x and y position between the red (reference)

15   centroid data and the green and blue data indicates the

amount of adjustment of the green and blue images that is

required to converge the image.

Focus for each primary color is accomplished by

processing the three horizontal data arrays previously

20   chosen by the user. After normalizing the data, a

single-sided, scaled power spectrum of the array data is

derived. Focus criteria are determined by summing the

elements of the power spectrum array to the right of the

first relative minima in the spectrum. This power

25   spectrum sum is then maximized for optimal focus.

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DESCRIPTION OF THE VIEWS OF THE DRAWINGS

The included drawings are as follows:

Figure 1a illustrates the three planes (red, green, and blue) for an out-of-convergence image. (prior art)

5 Figure 1b shows a row and column of non-converged pixels. (prior art)

Figure 2 shows a row and column of an out-of-focus image. (prior art)

Figure 3 shows a row and column of a subjectively focused
10 and converged image, based on operator's discretion. (prior art)

Figures 4a and 4b are diagrams indicating where test images are taken in the image's field-of-view.

Figure 4c is a diagram of an un-converged image showing
15 the x and y deltas (Δ).

Figure 4d is a diagram of a converged image.

Figure 5 is a drawing showing how the horizontal and vertical waveforms for the selected row and column are generated.

20 Figure 6 is a sketch of the differing red, green, and blue waveforms.

Figure 7 describes the waveform's 90% amplitude level where the pulse width is measured.

Figure 8a indicates the desired waveform's centroid.

25 Figure 8b indicates a false waveform centroid.

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Figure 8c illustrates the method for avoiding false

waveform centroid measurements.

Figures 9a, 9b and 9c illustrate the method of averaging

the waveforms for multiple cuts across a pixel.

5   Figure 10a is the Fast Fourier Transform (FFT) for a

horizontal pulse with sharp edges.

Figure 10b illustrates the power sum determined in the

tail of the FFT.

Figure 11a shows an out-of-focus image.

10   Figure 11b shows an image focused using the method of

this invention.

Figures 12a and 12b illustrate well-focused and poorly-

focused waveforms, respectively.

Figures 12c and 12d show the waveforms of Figures 12a and

15   12b normalized to level 255.

Figure 13a is a block diagram of the automated

convergence and focus system of this invention.

Figure 13b shows typical viewing window locations for the

automated convergence and focus system of this

20   invention.

Figure 14 is a sketch of a typical monitor screen showing

the automated convergence data of this invention.

Figure 15 is a sketch of a typical monitor screen showing

the automated focus data of this invention.

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Figure 16 is a diagram of the data format used in the
automated convergence and focus system of this
invention.

Figure 17a is a portion of a flow chart showing the
5   algorithm used for the automated focus and
convergence operation.

Figure 17b is a portion of a flow chart showing the
algorithm used for the automated focus and
convergence operation.

10   Figure 17c is a portion of a flow chart showing the
algorithm used for the automated focus and
convergence operation.

Figure 17d is a portion of a flow chart showing the
algorithm used for the automated focus and
15   convergence operation.

Figure 17e is a portion of a flow chart showing the
algorithm used for the automated focus and
convergence operation.

DETAILED DESCRIPTION

The method and system of this invention provide an objective tool for measuring the convergence and focus criteria of a projected image. In addition, lens

5   aberrations caused by lateral color shift are programmatically corrected.

The method for objectively converging the primary color images, typically red, green, and blue, involves capturing a magnified snapshot from several locations

10 across the field-of-view of the picture and separating this data into a separate image for each of the modulators.

While two or three captured images are enough to perform the convergence and focus operations, additional

15 images improve the process and provide better results. Typically five captured images are used. Each captured image typically is 640x480 pixel, 24-bit color image. The captured images are separated into three 8-bit images, one for each modulator and typically are stored

20 in DIB format. The modulators typically each provide a primary color image, such as red, green, and blue images, simplifying the separation process. Although this disclosure is in terms of the use of five 640x480 24-bit images, each dissolved into three 8-bit images, it should

25 be understood this is for purposes of illustration and

not for purposes of limitation. Other image resolutions,
bit-depths, and numbers of images and modulators are also
applicable to the processes taught herein.

    After capturing the images, a line and column of

5   interest are chosen from the file and the resulting three
horizontal (line) data arrays (Red, Green, and Blue) and
three vertical (column) data arrays are used to determine
the horizontal and vertical center-points of the three
(Red, Green, and Blue) pixels. Using the Red pixel

10   (optional selection) as a reference, the convergence
adjustment is calculated by measuring the differences in
the x and y dimensions between the Green and Blue pixel's
center-points and the Red reference pixel's center-point.
The green and blue center-points can then be moved to

15   overlay the red center-point, thereby converge the image.

    In the method, a row and column grid pattern is
turned ON in the projected image, as shown in Figure 4a.
For example, every 16th row and column of pixels might be
turned ON. A magnified 640x480 size image is then

20   captured around one of the grid pattern intersections.
Figure 4b is a diagram showing the locations 41-45 where
the five magnified 24-bit snapshots (A-E) are taken
across the field-of-view 40 of the picture. These
locations can vary, for example as shown by the dotted

25   line squares 48. A line 46 and column 47 of data is

chosen for each of the five snapshots for use in
converging the picture. The conditions are established
by turning ON only the pixels in the chosen row and
column over the area of the snapshot.

5   For each of the five snapshots, a 24-bit DIB data
file is separated into three 8-bit 640x480 data arrays,
one representing each of the three primary colors, red,
green, and blue. Figure 4c is a diagram of an overlay of
three un-converged red-green-blue images taken from the
10   same row and column in the snapshot. Any of the three
images could be used as a reference image, for example
red in the diagram. The x and y distances (ΔXg and ΔYg)
are then measured between the green row and column
intersection 402 and the red (ref) intersection 401 as
15   indicated and likewise the x and y distances (ΔXb and
ΔYb) are then measured between the blue row and column
intersection 403 and the red (ref) intersection 401. The
images from the green 402 and blue 403 SLM's can then be
adjusted to overlay the image from the red 401 SLM as
20   indicated in Figure 4d, where the red, green, and blue
images are converged 405.

       Figure 5 shows the details of the method used in
converging the red, green, and blue images. Given one of
the snapshots 50, consisting of a magnified row 51 and
25   column 52 of ON pixels, the pixel 59 of interest is

chosen by the placement of the horizontal and vertical

cursors (lines) 55 and 56, respectively. The data is

then sampled to provide the horizontal row and vertical

column waveforms 53 and 54, respectively, for the

5   selected pixel. The 24-bit image is separated into three

8-bit images (red, green, and blue) that are processed

individually. When the snapshot area is scanned for each

of the three 8-bit images at the selected pixel location,

the amplitude of the horizontal and vertical output

10   signals 53-54 will go from 0 volts to a positive value

(example: 0 to 5 volts) in the area of the selected

pixel, as shown. The method involves measuring the width

of these two pulses (horizontal 53 and vertical 54) and

then determining the center of each pulse. The point

15   where these two lines 55-56 intersect corresponds to the

centroid of the pixel for a given color (red, green, or

blue).   In the case of a typical micromirror, there is a

hole 57 located at the center of each pixel, where the

mirror connects to its support post, which causes a dip

20   58 in the waveform. This dip 58 can complicate the

process of locating the center of the waveform.

In locating the center of a row or column of pixels,

there can be several complications involved. First,

there is the dip at the center top of the waveform

25   discussed above. Then there is the fact that waveforms

representing the three colors each may have a somewhat

different shape, as illustrated in Figure 6. The red

waveform 60 is the closest to being ideal and is

therefore preferred as the reference to which the green

5   and blue images are adjusted. The green pulse 61 is

slightly wider than the red pulse 60. The blue pulse 62

is also wider and tends to flare out even more at the

lower levels. All these areas of complication have to be

contended with in the process of converging the image.

10   Figure 7 illustrates the method for overcoming the

problems created by the amount of flaring of the three

pulses at the lower levels. The red 70, green 71, and

blue 72 pulses are shown along with three lines 73-75

which represent the 10%, 50%, and 90% amplitude levels,

15   respectively. The method is to first normalize the three

pulse heights so as to have the same amplitude (255

quantization level) and then to measure the pulse widths

at the 90% amplitude level 75. This places the point of

measurement above most of the flaring and as a result

20   provides accurate pulse widths. From these pulse widths

the center of the three primary color pixels (red, green,

and blue) is determined.

Figure 8a is a sketch of an ideal pulse 80, which

represents the pixel width, with the pulse width being

25   measured at the 90% level 81 and the center of the pixel,

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indicated by line 82, falling directly through the dip in the waveform. However, as shown in Figure 8b it is possible for the dip 803 at the top of the pulse 800 to fall to or below the 90% level 801 and as a result for

5   the centerline 802 to be established in the center of one of the side lobes 804 instead of at the actual center of the pulse. The method used to overcome this potential problem is described in Figure 8c. Here three levels are determined for the pulse 810; i.e., (i) at the 90% level

10   811 on the leading edge, (ii) at the 10% level 812 on the trailing edge, and (iii) at the 90% level 813 on the trailing edge. The method for finding the center of the pulse is to first find the 90% level 811 on the leading edge, to go over the top of the pulse and down the

15   trailing edge to the 10% level 812, and then back up the trailing edge to the 90% level 813. The width of the pulse is then measured as the difference between the leading edge 90% level 811 and the trailing edge 90% level 813. The center of the pixel is shown by the line

20   814 at the mid-point of this difference. This approach avoids the possibility of making the measurements on one of the side lobes.

To this point the discussion has centered around a single scan taken through the center of a pixel. In

25   order to improve the accuracy, multiple sweeps (up to 20

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passes) are taken across the pixel in both the horizontal and vertical direction and an average of these pulses is used to make the calculations, as described in Figure 9. Figures 9a & 9b indicate how multiple scans are made

5 across a pixel 900 with scans 902 being on one side of the pixel center hole 901, other scans 903 through the area of the center hole 901, and additional scans 904 on the other side of the pixel center hole 901. These scans, shown for a row of pixels, apply equally to scans

10 made across a column of pixels. For example, in the case where 20 scans are made per pixel, assume that

$$a = 1,$$
$$a + m = 10, \text{ and}$$
$$a + n + 1 = 20.$$

15 Figure 9c shows the results of averaging the scans. Here, waveforms 902 & 904, on either side of the pixel, do not exhibit a dip 905 at the peak amplitude while scans 903 through the center of the pixels do have the dip 905 at peak amplitude. The average pulse 906 tends

20 to reduce the effects of any flaring on the edges of the pulse across the pixel and reduces the size of the dip 907 at the top of the pulse 906. The convergence accuracy is improved by using this averaging approach.

Table 1 is an overview of the algorithm of this invention, used in converging the three SLM (red, green, and blue).

TABLE 1 - CONVERGENCE ALGORITHM

DETERMINE PIXEL WIDTH

DETERMINE PIXEL HEIGHT

DETERMINE PIXEL CENTER - X

DETERMINE PIXEL CENTER - Y

FIND HORIZONTAL LINE

FIND VERTICAL COLUMN

SET (ALIGN) LINE AND COLUMN

The method used for the automated focusing of a projected image, under varying illumination conditions, is very difficult. However, it is possible to adjust the focus of the optics to an optimal number during the assembly phase of a projector. The method disclosed in this invention does this and can be used to assure that the focus parameter for shipped projector products are optimally focused and meet specification. The user of the projector can then manually focus the projector to match the brightness and other environmental conditions for a particular application.

In the automated focus method disclosed herein, focus for each color (red, green, and blue) is accomplished by processing the three horizontal data

arrays previously used in converging the pixels. After
the data is normalized, a single-sided, scaled power
spectrum of the data array is derived. Focus criteria
are then determined by summing the elements of the power
5   spectrum array to the right of the first relative minima
in the spectrum. As the optics are adjusted, the value
of the summed power spectrum is observed until a power
sum maximum value is found.

Figure 10a illustrates a typical Fast Fourier
10   Transform (FFT) 10 taken for the horizontal pulses with
relative sharp edges, as shown earlier in Figure 6. The
power spectrum is the area 11 under the curve and is
determined by adding the discrete values under the curve.
By maximizing this sum the focus can be controlled. In
15   practice, it was found that the sensitivity of the focus
adjustment could be improved by maximizing the area 101
in the tail of the FFT curve 100 to the right of the
first minima 102, as shown in Figure 10b. Figure 11a
shows an out-of-focus image and Figure 11b shows the same
20   image focused using the method of this invention.

As illustrated by Figure 12, focus is dependent on
the light levels. Figures 12a and 12b show well focused
and poorly focused, low light level pulses, respectively.
Due to the sharp rise and fall times of the well focused
25   pulse of Figure 12a, there is more area 101 in the tail

100 of the power spectrum (Figure 10b) curve then there
is for the more rounded edges of the poorly pulses of
Figure 12b. To reduce the effects of this problem, the
pulses are first normalized to level 255 (maximum 8-bit

5 level) before processing the data array, as shown in
Figures 12c and 12d, respectively.

Table 2 is an overview of the algorithm of this
invention, used in focusing the image.

TABLE 2 - FOCUS ALGORITHM

10 USING CAPTURED DATA

PERFORM SINGLE-SIDED FFT

DETERMINE MAX-MIN

FIND FIRST MINIMA OF ARRAY

SUM ARRAY ELEMENTS TO RIGHT OF MINIMA

15 Figure 13a is a system block diagram for carrying
out the convergence and focus methods of this invention.
Five Cameras 130-134 are used to store data from
magnified views at the selected locations across the
field-of-view; for example, locations at the upper left

20 (UL) 1300, upper right (UR) 1310, lower left (LL) 1320,
lower right (LR) 1330, and center (C) 1340 of the field,
as indicated in Figure 13b. The system is comprised of
the cameras 130-134, a video multiplexer (MUX) 135, a
frame grabber 136, a computer 137, and a viewing monitor

25 138.

Figure 14 illustrates a typical convergence screen 140 as seen by the operator on the monitor 138. This screen example shows the five sampling windows 141-145. In each window, the center of the pixel height and width

5   is displayed in windows 146 and 147, respectively.

Figure 15 illustrates a typical focus screen 150 as seen by the operator on the monitor 138. This screen example shows the pixel waveforms 151-155 for each pixel. The power spectrum value is displayed for each pulse in a

10   window (example, window 157). Lights indicating the best focus 158 and Red (reference) focus 159 are also included.

Figure 16a shows the format for storing the data for each selected pixel in the computer's 137 memory. First,

15   the 24-bit (B, G, R) image is stored as a BMP file. This file consists of a header 160 followed by the blue 1601, green 1602, and red 1603 data for horizontal pixel 0 through 639 (161, 162) of line 0 (163). This process is repeated over and over for lines 1 through 479 (164).

20   The 24-bit data is then separated into the three R, G, B 8-bit data files, as shown in Figure 16b. The file format of the data for each of the primary colors starts with a header 165 and a look-up-table (LUT) 166. The data then follows for pixel 0 through 639 for line 0

25   (167) through 479 (168).

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In operation, the data from this system is used to
converge and focus the red, green blue images. Aligning
the three SLM's to provide proper convergence could be
done using fly-in-place robots, or other automated

5   techniques, or even by manual adjustment. The optical
focus is adjusted to provide a maximum power spectrum
summation value.

Appendix A gives a more detailed listing of the
pseudo-code for the convergence and focus algorithm of

10   this invention.

The same techniques described herein for a 3-SLM
application apply as well to a 2-SLM system.

While this invention has been described in the
context of preferred embodiments, it will be apparent to

15   those skilled in the art that the present invention may
be modified in numerous ways and may assume embodiments
other than that specifically set out and described above.
Accordingly, it is intended by the appended claims to
cover all modifications of the invention that fall within

20   the true spirit and scope of the invention.

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